HOT SPOTS ON EARTH, VENUS, AND MARS: SPHERICAL HARMONIC SPECTRA

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INTRODUCTION. The distribution of large intraplate magmatic centers is now known for the three largest terrestrial planets [18]. Significant differences in the global geologic characteristics of Earth, Venus, and Mars were anticipated prior to these new observations [1] based on their different global hypsometries [2] and potentially different thermal histories [3]. In this study, we assess the spherical harmonic spectra of large magmatic centers on the terrestrial planets and show that, despite the known dissimilarities in global geology and surface ages, Venus, Earth, and Mars share some large-scale similarities in the arrangement of physically large and magmatically productive volcanic centers (hot spots).

CHARACTERISTICS OF HOT SPOT VOLCANISM . Volcanic centers on Venus were identified from geologic interpretation of synthetic aperture radar images returned by the Magellan spacecraft [4]. Global reconnaissance of over 1700 volcanic centers [5], and the results of preliminary mission science reports [6] were used to establish the location of all major volcanic centers on Venus and their relationship to global geologic characteristics. Similar maps of the distribution of volcanic centers and their relation to global geologic characteristics were prepared from existing data for Earth and Mars as discussed below. In view of the differences from planet to planet in morphological characteristics of the major magmatic centers that might be identified as hot spots, it is first necessary to justify the selection of the sets for each planet.

Volcanic and magmatic centers on Venus larger than 100 km in diameter were selected for consideration and analysis as only the largest of these volcanic edifices are likely to represent long-term centers of anomalous melting and repeated eruptions over extended periods of time comparable to that characterizing major centers of volcanism on Earth and Mars.

Large volcanic centers on Earth occurs in two fundamental settings: plate boundary and intraplate. Because plate boundaries associated with mobile tectonics are not present on Venus or Mars, the mapped distribution of "intraplate" or "hot spot" volcanism on Earth (Figure 1B) is considered appropriate for comparison with the distribution of volcanism on Venus and Mars. Some confusion exists about the exact definition of a "hot spot" and the degree to which the definition and identification is to be based on observed surface characteristics (e.g., volcano tracks) or inferred subsurface origins (e.g., plumes). The consensus view of hot spot descriptions were merged with additional geophysical criteriua [7] in order to arrive at a list of hot spots that agreed with previous usage and that could also be supported on the basis of numerical arguments. Apart from their distinctive locations and volumes, hot spot volcanism and plate boundary volcanism differ in a variety of significant physical and petrologic characteristics that facilitate their discrimination at statistically significant levels. One class includes hot spots that are typically characterized by tracks of extinct volcanoes and which are correlated with long-wavelength geoid anomalies (harmonic degree 2-10). This association with low harmonic degree characteristics of the global topographic and gravity fields together with their distinctive petrologic characteristics are interpreted

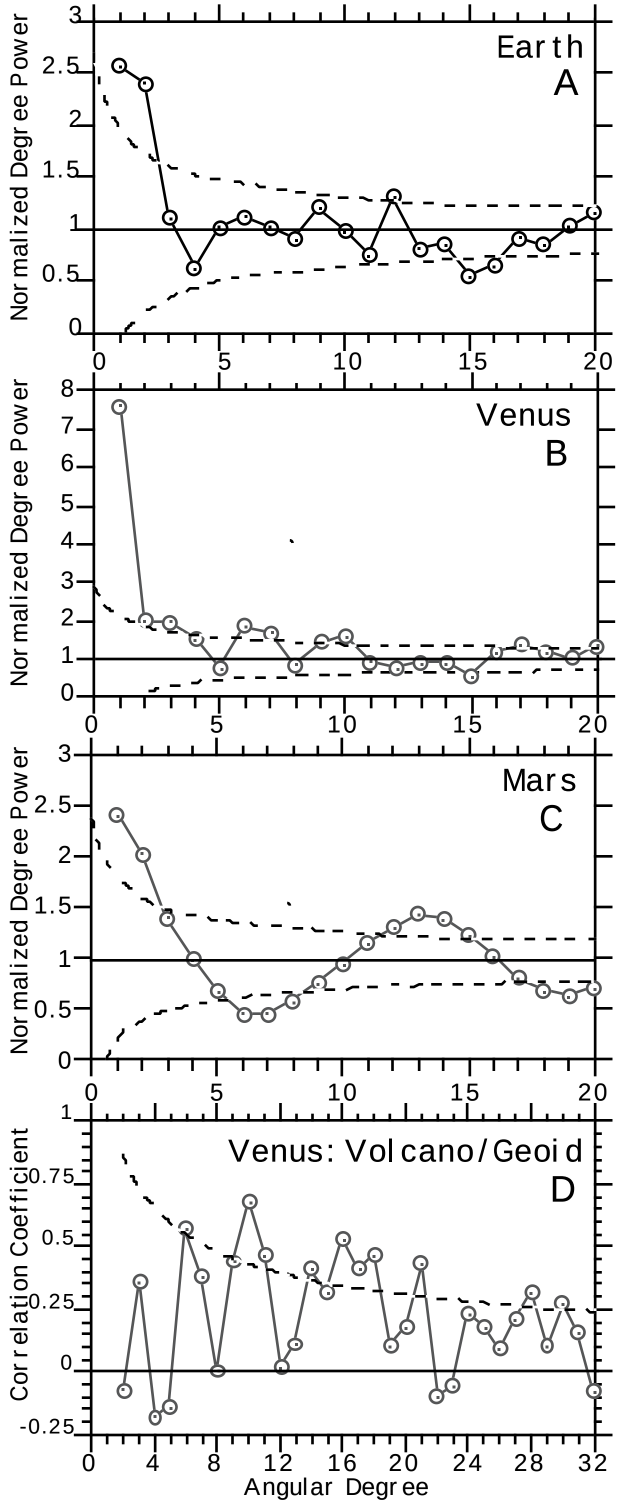

Figure 1. A-C . Harmonic power versus angular degree for hot spots on three terrestrial planets. Dashed line: 95%

confidence limit on uniformity. **D.** Correlation between hotspot distribution and geoid for Venus.

to be a consequence of a sublithospheric and deep-mantle, origin. The list of active hot spots from [8] compiled by Richards et al [9] satisfies most of the criteria determined in Marzoochi and Mulargia's study.

The choice of which volcanic centers to include in a martian hot spot list is much simpler as there are relatively few large volcanoes on Mars, each of which is large by either Venus or Earth standards. Volcanic centers on Mars occur in three settings, the Tharsis region, which is characterized by a hemispheric topographic rise or swell, and is the largest concentration, and the Elysium region and Hellas basin region, both of which occur in the opposite hemisphere.

Finally, consideration must be given to the differences in age of the surfaces of the three planets and corresponding differences in the accumulation period of each population of hot spots. Current estimates for the global surface age of Venus, approximately 500Ma [10], suggest s that the record of volcanism o Venus is comparable to the age of the current hot spot population on Earth [approximately 200 Ma [11]. Thus the total accumulated hot spot population for Earth and Venus are comparable within a factor or two. The time interval recorded in the population of large volcanoes on Mars may be much greater. The oldest volcanoes, those of the Hellas and related highland provinces are estimated at 3.7 to 3.1 Ga [12], whereas the volcanoes of the Tharsis region range from 1.5 to 0.1 Ga [13]. The absolute number of volcanoes on Mars is low and reflects the lower global volume-rate of magma production [14] throughout its geologic history, estimated to be two to three orders of magnitude less than that on Earth or Venus. Although there appears to be a great range in age of volcanism on Mars, the relatively stable surface combined with the declining production rates with time suggest that the population of volcanoes on Mars represents the only cycle of hot spot production on that planet and that mantle events or surface tectonic responsible for the population are not overprinted. Thus there are a variety of reasons for comparing hot spots on Earth with large magmatic centers on Venus and large volcanoes on Mars.

The observed distribution based on this selection has been discussed previously [15]. In general, each planet shows a similar qualitative bipolar arrangement of volcanic centers with three common characteristics: (i) a *primary group*, defined as a significant concentration of volcanic and magmatic centers in which more than one-half of the global population occurs within less than 30% of the global area; (ii) a region peripheral to this concentration in which the regional density is less than or close to that expected for a randomly distributed population, and (iii) a distal region, or *secondary group*, occupying about 30% of the global area in which the density approaches that expected for a globally uniform distribution.

SPHERICAL HARMONIC SPECTRA. For the analysis, each volcano was weighted according to fluxes or volume: For Earth, erosion introduces potential variations, so the estimated fluxes of hot spots [7] were used to establish magnitude data; for Mars, volumes were calculated from existing topographic data; and for Venus, a model for the "average" relief and slope was used based on an extensive survey of large volcano relief and width characteristics [ref]. The spectra for all three planets were then determined out to degree 20. The results (Figure 1) indicate that all three planets are similar in that they are dominated by degrees 1 and/or 2 and have spectra that tend to peak at degree 1 (hemisphericity).

Earth has sub-equal degree 1 and 2 power. This is a combination of the flux high over the Pacific (degree 1), the minor flux high over Africa (degree 2) and the banding about the equator (also degree 2). Venus is dominantly degree 1 with greatest volume within the Beta-Atla-Themis area and lowest volume in the Aphrodite Terra region. Beyond degree 1, the spectrum for Venus is whiter than that of Earth. The hot spot distribution for Mars is similar to Earth in that degrees 1 and 2 dominate. The distribution of volume for Earth differs from a random (uniform) pattern only at degrees 1 and 2. Mars differs at many degrees - the product of clustering which depends strongly on how one constructs the data set. Grouping overlapping or related volcanoes into single units (summing volumes) would result in a whiter, more random spectrum (at high degree). Venus has many degrees that are not random. In terms of the uniformity of hotspot distribution, Mars and Venus differ significantly from Earth. Both Mars and Venus have more energy at high degree, implying less deep-seated (long-wavelength) control over volcanism.

Some insight into the origin of the distribution for Venus may be gained by considering the correlation with geoid. Correlation at high degree is expected since Venus' topography and geoid are strongly correlated at short wavelengths. The highest correlation (degree 10) may be associated with the principal volcanic rises, which are known to have large geoid signatures [16]. If the large concentration in Beta-Atla-Themis is the reflection of a deep upwelling as previously suggested [5], the absence of significant correlation of Venusian volcanoes with geoid at low degrees is evidence that the current hemispheric arrangement is relict and does not reflect currently active processes. This result is consistent with the observations of Grosfils and Head [17] who noted that the large scale patterns of surface strain surrounding the Beta-Atla-Themis concentration was emplaced concurrently with most of the volcanism.

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